CS195: Computer Vision

Discrete Probability Distribution

Joint probability distribution
Marginal probability distribution
Conditional probability distribution
Bayes Rule

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Probability Basics

- **Probability Distribution**
- **Joint Probability Distribution**
- **Marginal Probability Distribution**
- **Conditional Probability Distribution**
- **Bayes Rule**

Probability Basics

- **Probability Distribution**
  - Discrete Probabilities
  - Continuous Probabilities

In this lecture, we are going to cover only distributions for discrete events; continuous distributions will be covered in the next lecture.

- **Probability Distribution and Random Variable**
  - Probability distribution is a function which will depend on a random variable eg, X
  - If the random variable X takes discrete values then you get discrete probabilities

Random Number

- Random numbers are useful many applications:
  - Simulating a coin toss — random flipping of head or tail
  - Simulating a dice roll — random roll of one of six sides
  - Simulating a card shuffling - randomly selecting cards (out of 52)

- Python provides library to generate random numbers
  - You can import random module to get access to random number generating functions

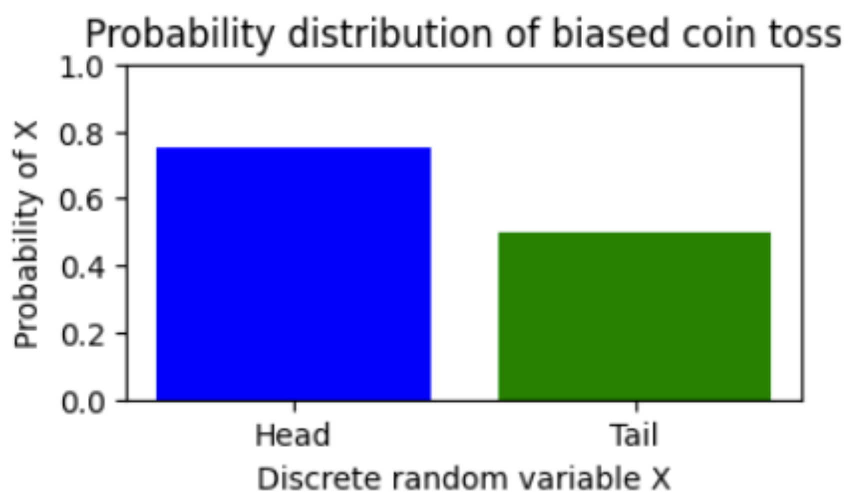
```
import random

rand_number = random.randint(1, 10)
print(rand_number)
```

Probability Basics

- **Discrete Probability Distribution (1 dimensional event):**
  - Let's assume *X* is random variable which can take discrete values
  - P(*X*) is a function that maps from all possible values of X to the probability of the corresponding event. For example:
    - X is a random variable
    - The sample space is the set of possible value that X can take.
    - There is probability assigned to each element of the sample space.
    - Eg, X is a random variable for coin toss event, hence X can take one of the 2 values from the sample space *{Head, Tail}*

$$P(X = Head) = 0.75$$

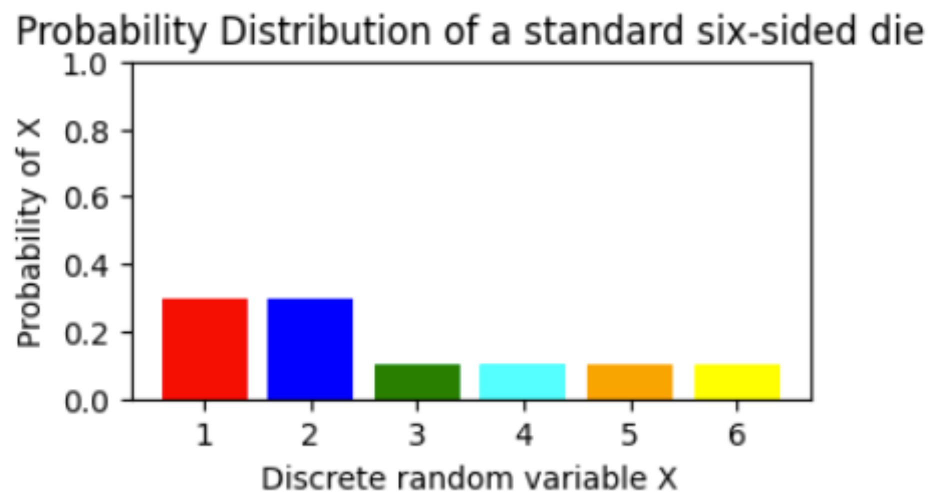
$$P(X = Tail) = 0.25$$



Probability Basics

- **Discrete Probability Distribution (1 dimensional event):**
  - Let's assume *X* is random variable which can take discrete values
  - P(*X*) is a function that maps from all possible values of X to the probability of the corresponding event.
    - X is a random variable which can take one of the 6 values for a standard six-sided die, ie, the sample space of X: *{1, 2, 3, 4, 5, 6}.*

$$P(X=1)=0.3$$
$$P(X=2)=0.3$$
$$P(X=3)=0.1$$
$$P(X=4)=0.1$$
$$P(X=5)=0.1$$
$$P(X=6)=0.1$$



Probability Basics

- **Discrete Probability Distribution (multi-dimensional event):**
  - What about when we have more than two random variables?
    - both random variables may take discrete values.
  - Let's assume there are two random variables, X and Y, each of which can take on discrete values.
  - Essentially, we are transitioning from a one-dimensional probability distribution to a higher-dimensional space. Let's start with a 2-dimensional probability distribution.

Probability Basics

- Probability Distribution
- **Joint Probability Distribution**
- Marginal Probability Distribution
- Conditional Probability Distribution
- Bayes Rule

Probability Basics

- **Discrete Probability Distribution (2 dimensional event):**
  - Let's assume there are two random variables, X and Y, each of which can take on discrete values.

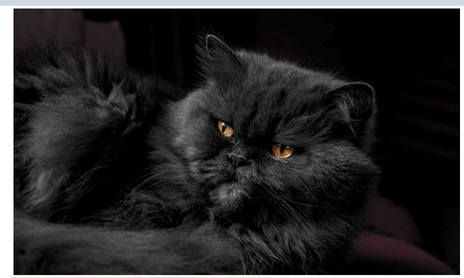
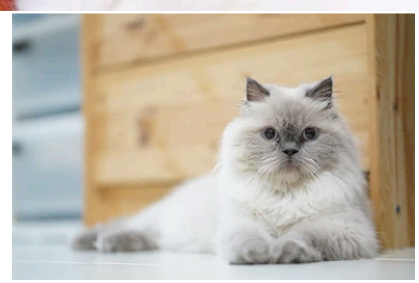
1st dimension →

2nd dimension ↓

	Discrete value of 1st random variable X	Discrete value of 1st random variable X
Discrete value of 2nd random variable Y		
Discrete value of 2nd random variable Y		

Probability Basics

- **Discrete Probability Distribution (2 dimensional event):**
  - Let’s assume that you are planning to adopt a cat but can’t decide which breed and color to pick from. You were blind-folded and decided to randomly pick one of the following possible cats

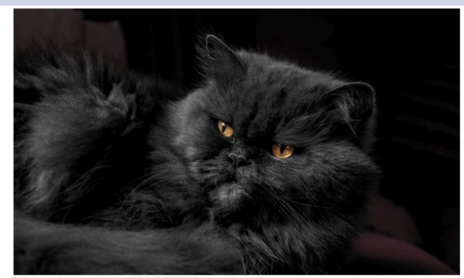
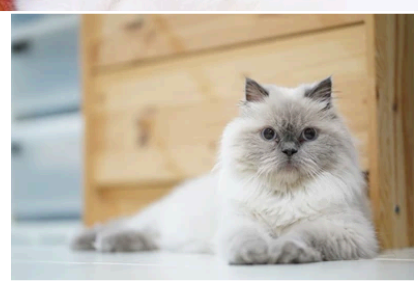
	white	black
Persian		
Himalayan		

Probability Basics

- **Discrete Probability Distribution (2 dimensional event):**
  - What is the probability that you picked
    - Persian cat?
    - Himalayan cat?

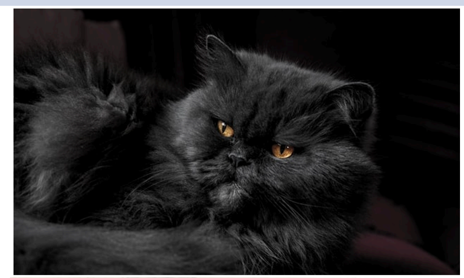
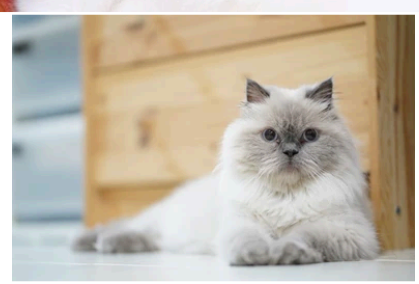
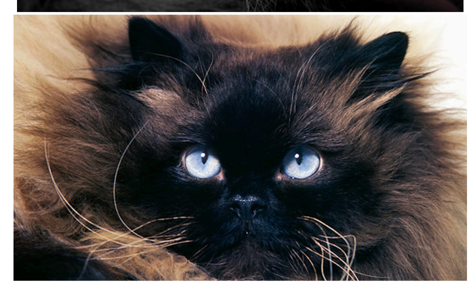
1st dimension

2nd dimension

	white	black
Persian		
Himalayan		

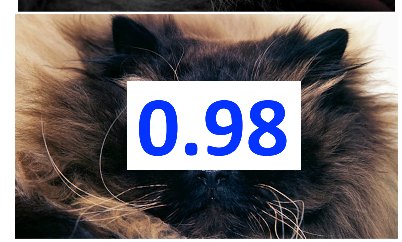
Probability Basics

- **Discrete Probability Distribution (2 dimensional event):**
  - X = random variable indicating color
  - Y = random variable indicating breed
  - What is P(X=white, Y=Persian)?

	white	black
Persian		
Himalayan		

Joint Probability Distribution

- Sample space is set of all possible outcomes of the random variable
  - X = random variable indicating color of the cat
  - Y = random variable indicating breed of the cat
- The full joint probability distribution assigns a probability to each element of the sample space

	white	black
Persian	 0.08	 0.02
Himalayan	 0.01	 0.98

Joint Probability Distribution

- Sample space is set of all possible outcomes of the random variable
  - X = random variable indicating color of the cat
  - Y = random variable indicating breed of the cat

- The full joint probability distribution assigns a probability to each element of the sample space. You can also list the probabilities of the sample space in the format below:

X	Y	P(X,Y)
White	Persian	?
White	Himalayan	?
Black	Persian	?
Black	Himalayan	?

Joint Probability Distribution

- The joint probability distribution expresses probability distribution of observing varied instance of (x, y) where some paired outcome occurs more frequently than others
  - X = random variable with three discrete values {a, b, c}
  - Y = random variable with three discrete values { α , β , γ }
- The joint probability distribution P(X, Y) is expressed using the table

	X=a	X=b	X=c
Y= α	0.1	0.05	0.1
Y= β	0.1	0.3	0.1
Y= γ	0.05	0.05	0.15

Probability Basics

- Probability Distribution
- Joint Probability Distribution
- **Marginal Probability Distribution**
- Conditional Probability Distribution
- Bayes Rule

Marginal Probability Distribution

- The marginal probability distribution expresses probability distribution of any single random variable from a joint probability distribution by summing over all other variables

$$P(X) = \sum_{y} P(X, Y = y)$$

	X=a	X=b	X=c
Y= α	0.1	0.05	0.1
Y= β	0.1	0.3	0.1
Y= γ	0.05	0.05	0.15

Marginal Probability Distribution

	X=a	X=b	X=c
Y=α	0.1	0.05	0.1
Y=β	0.1	0.3	0.1
Y=γ	0.05	0.05	0.15

$$P(X) = P(X, Y = \alpha) + P(X, Y = \beta) + P(X, Y = \gamma)$$

- Aggregating individual marginal probability values into a histogram to make the probability distribution as follows:

  [P(X=a), P(X=b), P(X=c)]

- Marginal distribution has the following interpretation — "It finds the probability of X happening regardless of Y taking any value of α β γ

Exercise 1: Marginal Probability Distribution

	X=a	X=b	X=c
Y=α	0.1	0.05	0.1
Y=β	0.1	0.3	0.1
Y=γ	0.05	0.05	0.15

$$P(X) = P(X, Y = \alpha) + P(X, Y = \beta) + P(X, Y = \gamma)$$

- Find the marginal distribution P(X)?

$$\boxed{\begin{aligned} P(X = a) &= ? \\ P(X = b) &= ? \\ P(X = c) &= ? \end{aligned}}$$

Solution: Marginal Probability Distribution

Compute along this direction

	X=a	X=b	X=c
Y=α	0.1	0.05	0.1
Y=β	0.1	0.3	0.1
Y=γ	0.05	0.05	0.15

$$P(X) = P(X, Y = \alpha) + P(X, Y = \beta) + P(X, Y = \gamma)$$

- Find the marginal distribution P(X=a)?

$$P(X = a) = P(X = a, Y = \alpha) + (X = a, Y = \beta) + (X = a, Y = \gamma)$$

$$= ?$$

Solution: Marginal Probability Distribution

	X=a	X=b	X=c
Y=α	0.1	0.05	0.1
Y=β	0.1	0.3	0.1
Y=γ	0.05	0.05	0.15

$$P(X) = P(X, Y = \alpha) + P(X, Y = \beta) + P(X, Y = \gamma)$$

- Find the marginal distribution P(X=a)?

$$\begin{aligned} P(X = a) &= P(X = a, Y = \alpha) + (X = a, Y = \beta) + (X = a, Y = \gamma) \\ &= 0.1 + (X = a, Y = \beta) + (X = a, Y = \gamma) \\ &= 0.1 + 0.1 + (X = a, Y = \gamma) \\ &= 0.1 + 0.1 + 0.05 \\ &= 0.25 \end{aligned}$$

Solution: Marginal Probability Distribution

Compute along this direction

	X=a	X=b	X=c
Y=α	0.1	0.05	0.1
Y=β	0.1	0.3	0.1
Y=γ	0.05	0.05	0.15

$$P(X) = P(X, Y = \alpha) + P(X, Y = \beta) + P(X, Y = \gamma)$$

- Find the marginal distribution P(X=b)?

$$P(X = b) = P(X = b, Y = \alpha) + (X = b, Y = \beta) + (X = b, Y = \gamma)$$

$$= ?$$

Solution: Marginal Probability Distribution

	X=a	X=b	X=c
Y=α	0.1	0.05	0.1
Y=β	0.1	0.3	0.1
Y=γ	0.05	0.05	0.15

$$P(X) = P(X, Y = \alpha) + P(X, Y = \beta) + P(X, Y = \gamma)$$

- Find the marginal distribution P(X=b)?

$$P(X = b) = P(X = b, Y = \alpha) + (X = b, Y = \beta) + (X = b, Y = \gamma)$$

$$= 0.05 + (X = b, Y = \beta) + (X = b, Y = \gamma)$$

$$= 0.05 + 0.3 + (X = b, Y = \gamma)$$

$$= 0.05 + 0.3 + 0.05$$

$$= 0.40$$

Solution: Marginal Probability Distribution

Compute along this direction

	X=a	X=b	X=c
Y=α	0.1	0.05	0.1
Y=β	0.1	0.3	0.1
Y=γ	0.05	0.05	0.15

$$P(X) = P(X, Y = \alpha) + P(X, Y = \beta) + P(X, Y = \gamma)$$

- Find the marginal distribution P(X=c)?

$$P(X = c) = P(X = c, Y = \alpha) + (X = c, Y = \beta) + (X = c, Y = \gamma)$$

$$= ?$$

Solution: Marginal Probability Distribution

	X=a	X=b	X=c
Y=α	0.1	0.05	0.1
Y=β	0.1	0.3	0.1
Y=γ	0.05	0.05	0.15

$$P(X) = P(X, Y = \alpha) + P(X, Y = \beta) + P(X, Y = \gamma)$$

- Find the marginal distribution P(X=c)?

$$P(X = c) = P(X = c, Y = \alpha) + (X = c, Y = \beta) + (X = c, Y = \gamma)$$

$$= 0.10 + (X = c, Y = \beta) + (X = c, Y = \gamma)$$

$$= 0.10 + 0.10 + (X = c, Y = \gamma)$$

$$= 0.10 + 0.10 + 0.15$$

$$= 0.35$$

Marginal Probability Distribution

	X=a	X=b	X=c
Y=α	0.1	0.05	0.1
Y=β	0.1	0.3	0.1
Y=γ	0.05	0.05	0.15

$$P(X) = P(X, Y = \alpha) + P(X, Y = \beta) + P(X, Y = \gamma)$$

- Aggregating individual marginal probability values into a histogram to make the probability distribution as follows:

[P(X=a), P(X=b), P(X=c)]

[0.25, 0.40, 0.35]

It sums up to 1.0, which satisfies the property of a probability distribution.

- Marginal distribution has the following interpretation — "It finds the probability of X happening regardless of Y taking any value of α β γ

Exercise 2: Marginal Probability Distribution

Compute along these directions one after another

	X=a	X=b	X=c
Y=α	0.1	0.05	0.1
Y=β	0.1	0.3	0.1
Y=γ	0.05	0.05	0.15

$$P(Y) = P(X = a, Y) + (X = b, Y) + (X = c, Y)$$

- Similarly, can you find the marginal distribution P(Y)?

$$P(Y = \alpha) = ?$$
$$P(Y = \beta) = ?$$
$$P(Y = \gamma) = ?$$

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Probability Basics

- **Probability Distribution**
- **Joint Probability Distribution**
- **Marginal Probability Distribution**
- **Conditional Probability Distribution**
- **Bayes Rule**

Conditional Probability Distribution

- It tells us the relative propensity
- Conditional probability distribution of any single random variable *(eg, X)* conditioned on other variable's *(eg, Y)* value fixed to a particular value
- Conditional distribution has the following form:

$$P(X \mid Y = \alpha)$$

	X=a	X=b	X=c
Y=α	0.1	0.05	0.1
Y=β	0.1	0.3	0.1
Y=γ	0.05	0.05	0.15

- Individual terms of the conditional distribution has the following form:

We computed this marginal probability term earlier

$$P(X = a \mid Y = \alpha) = \frac{P(X = a, Y = \alpha)}{P(Y = \alpha)}$$

$$= \frac{P(X = a, Y = \alpha)}{P(X = a, Y = \alpha) + P(X = b, Y = \alpha) + P(X = c, Y = \alpha)}$$

If you don't recall, here is how it can be recomputed

Conditional Probability Distribution

- It tells us the relative propensity
- Conditional probability distribution of any single random variable *(eg, X)* conditioned on other variable's *(eg, Y)* value fixed to a particular value

	X=a	X=b	X=c
Y=α	0.1	0.05	0.1
Y=β	0.1	0.3	0.1
Y=γ	0.05	0.05	0.15

- In this example, you need to compute three conditional probabilities to form a valid distribution

$$P(X = a \mid Y = \alpha) = ?$$

$$P(X = b \mid Y = \alpha) = ?$$

$$P(X = c \mid Y = \alpha) = ?$$

Conditional Probability Distribution

- It tells us the relative propensity
- Conditional probability distribution of any single random variable *(eg, X)* conditioned on other variable's *(eg, Y)* value fixed to a particular value

	X=a	X=b	X=c
Y=α	0.1	0.05	0.1
Y=β	0.1	0.3	0.1
Y=γ	0.05	0.05	0.15

We computed this marginal probability term earlier

$$\boxed{P(Y=\alpha) = 0.25}$$

- In this example, you need to compute three conditional terms to make it a distribution

$$P(X=a \mid Y=\alpha) = \frac{P(X=a, Y=\alpha)}{P(Y=\alpha)}$$

$$P(X=b \mid Y=\alpha) = \frac{P(X=b, Y=\alpha)}{P(Y=\alpha)}$$

$$P(X=c \mid Y=\alpha) = \frac{P(X=c, Y=\alpha)}{P(Y=\alpha)}$$

Exercise 3: Conditional Probability Distribution

	X=a	X=b	X=c
Y=α	0.1	0.05	0.1
Y=β	0.1	0.3	0.1
Y=γ	0.05	0.05	0.15

$$P(X|Y = \alpha)$$

- Aggregating individual conditional probability values into a histogram to make the probability distribution as follows:

$$[P(X = a \,|\, Y = \alpha), P(X = b \,|\, Y = \alpha), P(X = c \,|\, Y = \alpha)]$$

Exercise 3: Conditional Probability Distribution

- It tells us the relative propensity
- Conditional probability distribution of any single random variable *(eg, X)* conditioned on other variable's *(eg, Y)* value fixed to a particular value

We computed this marginal probability term earlier

$$P(Y = \alpha) = 0.25$$

$$P(X = a \mid Y = \alpha) = ?$$

$$= \frac{P(X = a, Y = \alpha)}{P(Y = \alpha)}$$

$$= \frac{0.1}{P(Y = \alpha)}$$

$$= \frac{0.1}{0.25}$$

$$= 0.4$$

	X=a	X=b	X=c
Y=α	0.1	0.05	0.1
Y=β	0.1	0.3	0.1
Y=γ	0.05	0.05	0.15

Exercise 3: Conditional Probability Distribution

- It tells us the relative propensity
- Conditional probability distribution of any single random variable *(eg, X)* conditioned on other variable's *(eg, Y)* value fixed to a particular value

We computed this marginal probability term earlier

$$\boxed{P(Y=\alpha) = 0.25}$$

$$P(X=b\,|\,Y=\alpha) = ?$$

$$= \frac{P(X=b, Y=\alpha)}{P(Y=\alpha)}$$

$$= \frac{0.05}{P(Y=\alpha)}$$

$$= \frac{0.05}{0.25}$$

$$= 0.2$$

	X=a	X=b	X=c
Y=α	0.1	0.05	0.1
Y=β	0.1	0.3	0.1
Y=γ	0.05	0.05	0.15

Exercise 3: Conditional Probability Distribution

- It tells us the relative propensity
- Conditional probability distribution of any single random variable *(eg, X)* conditioned on other variable's *(eg, Y)* value fixed to a particular value

We computed this marginal probability term earlier

$$P(X = c \mid Y = \alpha) = ?$$

$$= \frac{P(X = c, Y = \alpha)}{P(Y = \alpha)}$$

$$\boxed{P(Y = \alpha) = 0.25}$$

$$= \frac{0.1}{P(Y = \alpha)}$$

$$= \frac{0.1}{0.25}$$

$$= 0.4$$

	X=a	X=b	X=c
Y=α	0.1	0.05	0.1
Y=β	0.1	0.3	0.1
Y=γ	0.05	0.05	0.15

Exercise 3: Conditional Probability Distribution

	X=a	X=b	X=c
Y=α	0.1	0.05	0.1
Y=β	0.1	0.3	0.1
Y=γ	0.05	0.05	0.15

$$P(X \mid Y = \alpha)$$

- Aggregating individual conditional probability values into a histogram to make the probability distribution as follows:

$$[P(X = a \mid Y = \alpha), P(X = b \mid Y = \alpha), P(X = c \mid Y = \alpha)]$$

$$[0.4, \qquad 0.2, \qquad 0.4]$$

Probability Basics

- **Probability Distribution**
- **Joint Probability Distribution**
- **Marginal Probability Distribution**
- **Conditional Probability Distribution**
- **Bayes Rule**

Bayes Rule

$$P(X,Y) = P(Y|X)P(X) = P(X|Y)P(Y)$$

$$P(Y|X)P(X) = P(X|Y)P(Y)$$

$$\begin{aligned} P(Y|X) &= \frac{P(X|Y)P(Y)}{P(X)} \\ &= \frac{P(X|Y)P(Y)}{\sum_y P(X,Y=y)} \\ &= \frac{P(X|Y)P(Y)}{\sum_y P(X|Y=y)P(Y=y)} \end{aligned}$$

Bayes' Rule

$$\boxed{P(Y|X) = \frac{P(X|Y)P(Y)}{P(X)}} = \frac{P(X|Y)P(Y)}{\sum_y P(X, Y = y)} = \frac{P(X|Y)P(Y)}{\sum_y P(X|Y = y)P(Y = y)}$$

Bayes' rule is useful when you want to know something about ***Y***, but all you can *directly* observe is ***X***

- This process is called Bayesian inference

Bayes' Rule

$$\boxed{P(Y|X) = \frac{P(X|Y)P(Y)}{P(X)}} = \frac{P(X|Y)P(Y)}{\sum_y P(X, Y=y)} = \frac{P(X|Y)P(Y)}{\sum_y P(X|Y=y)P(Y=y)}$$

$P(X)$ is called the evidence

$P(X|Y)$ is called the likelihood

We will often define the relationship between **y** and **x** in terms of conditional probability

$P(Y)$ is called the prior probability

It represents what we know about **y** before we consider **x**

$P(Y|X)$ is called the posterior probability

It represents what we know about **y** given **x**

If we know x has a distribution p(x) then p(y|x) is a more informative distribution